SWAMP

Sammamish/Washington Analysis and Modeling Program

LAKE WASHINGTON EXISTING CONDITIONS REPORT

September 2003

King County

Department of Natural Resources and Parks
Water and Land Resources Division

SWAMP

Sammamish/Washington Analysis and Modeling Program

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September 2003

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KING COUNTY

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ABBREVIATIONS

µg	micrograms
µmhos/cm	micromhos per centimeter (equivalent to microSiemens per centimeter)
AHOD	areal hypolimnetic oxygen deficit rate
ANOVA	Analysis of Variance
chl *a*	chlorophyll *a*
CSO	combined sewer overflow
DNRP	Department of Natural Resources and Parks
DO	dissolved oxygen
ESA	Endangered Species Act
ft	feet
ICP-MS	inductively coupled plasma mass spectrometry
km	kilometers
KCEL	King County Environmental Laboratory
L	liters
LIMS	Laboratory Information Management System
m	meters
MDL	method detection limit
meq/L	milliequivalents per liter
mg	milligrams
N	nitrogen
NOAA	National Oceanic Atmospheric Administration
P	phosphorus
PAH	polycyclic aromatic hydrocarbon
RDL	reporting detection limit
SD	standard deviation
SRP	soluble reactive phosphorus
SWAMP	Sammamish-Washington Analysis and Modeling Program
TN	total nitrogen
TP	total phosphorus

TSIs	trophic state indices
USEPA	United States Environmental Protection Agency
USFWS	United States Fish and Wildlife Service
UW	University of Washington
WAC	Washington Administrative Code
WRIA 8	Water Resource Inventory Area 8

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Executive Summary

The King County Department of Natural Resources and Parks, Water and Land Resources Division has developed the Sammamish-Washington Analysis and Modeling Program (SWAMP). The purpose of SWAMP is to assist wastewater capital planning, habitat conservation, salmon recovery, and watershed planning efforts by collecting information and by developing and using a set of scientific tools to better understand the Sammamish-Washington Watershed system. The *Lake Washington Existing Conditions Report* was produced under SWAMP and summarizes 12 years of water quality data collected as part of the Major Lakes Monitoring Program, another program within King County Department of Natural Resources and Parks, Water and Land Resources Division to monitor lake conditions.

The purpose of this study was to summarize water quality conditions and trends in Lake Washington from 1990 to 2001. The report describes how Lake Washington has responded over time to watershed activities, lake nutrient inputs, ecological interactions, and seasonal or year-to-year variability. Specifically, Lake Washington water quality data were analyzed to address the following objectives:

- To characterize the current status of the lake relative to standard ecological indicators, such as transparency (water clarity), dissolved oxygen (DO), total phosphorus (TP), and chlorophyll *a* (chl *a*).
- To identify current water quality differences between nearshore and deep open water (pelagic) areas of the lake.
- To identify water quality trends during the study period, with reference to historical conditions where applicable.
- To provide information for use in making future environmental management decisions that may impact the lake.

Data collected from 1990 through 2001 indicate that the quality of Lake Washington's water supports and is consistent with the lake's beneficial uses. Some of the major findings are as follows:

- Annual whole-lake volume-weighted mean TP concentrations ranged from 10 to 18 μg/L and were lower in the last 4 years of the study period. Trend analysis showed that there is a significant trend towards decreasing whole-lake TP concentrations from 1993 to 2001. Total phosphorus concentrations in the lake are indicative of mesotrophic conditions. The 10-year overall mean of the annual volume-weighted means was 14 μg/L. External loading of TP controls TP concentrations in the lake. Internal loading of phosphorus is not a significant part of the phosphorus (P) cycle in the lake.
- Dissolved oxygen concentrations and deficit rates indicate that Lake Washington is mesotrophic, which is an improvement from the 1950s and 1960s, when it was eutrophic.

- The annual chl *a* 12-year mean was 3.4 µg/L with a summer 12-year mean of 2.4 µg/L. These concentrations indicate that the lake is mesotrophic. Highest chl *a* concentrations occurred during spring with the usual bloom of diatoms, which were the most commonly occurring algae in Lake Washington. Spring chl *a* concentrations were significantly higher than chl *a* concentrations for other seasons.
- Whole-lake total nitrogen (TN) to TP ratios ranged from 13:1 to 30:1, indicating that P was limiting algal growth. There was a trend toward increasing TN:TP ratios in the lake from 1994 through 2001, which indicates that Lake Washington has become increasingly limited by P.
- Transparency has remained consistent from year to year, with an overall mean of 4.6 meters (m). Mean summer transparencies ranged from 3.5 to 5.6 m.
- Temperature of Lake Washington ranged from 7º to 9ºC in January, during the period of complete mixing every year. The maximum temperature in both nearshore and pelagic water was between 21.5º and 24.5ºC without an increasing trend. From 1993 to 2001 there was an increasing trend in seasonal and annual average water temperatures (epilimnetic and whole lake) that may be attributed to global climate change-related increases in air temperatures. The effect of this trend on lake biota is currently unknown.
- The annual volume-weighted whole-lake TN mean concentrations ranged between 175 and 340 µg/L. No significant trend in whole-lake annual TN was found.

Overall, Lake Washington has recovered from the eutrophic, over enriched state that existed in the 1950s to 1960s. The key to rapid recovery was the lake’s depth, which contained large stores of dissolved oxygen and the reduction in P loading that occurred with sewage diversion. The lake is sensitive to P loading, and the maintenance of present-day water quality is dependent on keeping P loading at or below current levels. Minimal development of the Cedar River basin has been a key factor in recovery and maintenance of lake water quality.

1. INTRODUCTION

1.1. Overview

The King County Department of Natural Resources and Parks, Water and Land Resources Division conducts an ongoing lake monitoring program that assesses water quality in Lake Washington, Lake Sammamish, and Lake Union. The Major Lakes Monitoring Program was designed to provide data that serves as a basis to evaluate the efforts in water quality improvements and protection made by the people of King County.

This report summarizes water quality conditions and trends in Lake Washington using 10 years of water quality data collected as part of the Major Lakes Monitoring Program. Data from this period were analyzed to develop a current conditions benchmark of lake water quality. This effort to assess water quality trends in Lake Washington was conducted under the Sammamish-Washington Analysis and Modeling Program (SWAMP) within King County's Department of Natural Resources and Parks, Water and Land Resources Division. The purpose of SWAMP is to assist wastewater capital planning, habitat conservation, salmon recovery, and watershed planning efforts by collecting information and by developing and using a set of scientific tools to better understand the Sammamish-Washington Watershed system. This report is the first of three reports to evaluate each of the three major lakes in the SWAMP study area. Existing conditions reports evaluating Lakes Sammamish and Union are in preparation.

1.1.1. Study Purpose

The purpose of this study is to evaluate the water quality data collected from 1990 through 2001 to describe and document how Lake Washington has responded over time to watershed activities, nutrient inputs, ecological interactions, and seasonal or year-to-year variability. Lake responses can vary from short-term variability due to seasonal weather patterns, to long-term responses due to watershed changes. These data will also be compared to available historical data and overall trends will be discussed.

Specifically, water quality data were analyzed with the following objectives:

- To describe the current status of the lake's quality relative to ecological indicators, such as transparency (water clarity), dissolved oxygen (DO), total phosphorus (TP), and chlorophyll *a* (chl *a*).
- To describe the trends in water quality during the study period, with reference to historical conditions where applicable.
- To describe current similarities and differences in water quality between nearshore (littoral) and deep open water (pelagic) areas of the lake.
- To provide information for use in making future environmental management decisions.

1.1.2. Report Presentation

This report presents the Lake Washington monitoring data from 1990 through 2001 and provides citizens, environmental managers, and scientists with access to the data. The main body of the report is organized around building an understanding of the lake based on the parameters studied. Following the Introduction, there is a brief discussion on Historical Water Column Conditions to illustrate what the water quality of the lake was prior to implementation of environmental management strategies aimed at improving and protecting lake water quality.

The Water Column Monitoring Background section provides a brief description of each water quality parameter studied and the methods for both collection and laboratory analysis. The results of the monitoring effort for 1990 through 2001 are presented in Section 4, Summary of 1990 to 2001 Monitoring Data. This section first presents a brief overview of the data results, followed by a more detailed discussion of each parameter and what can be learned about the lake status from these data. A Glossary of Terms and References precede the Appendices.

1.2. Lake Washington Characteristics

Lake Washington is the largest of the three major lakes in King County, and the second largest natural lake in the State of Washington (Figure 1). The lake is located within the watersheds drained by Issaquah Creek, the Sammamish River, and the Cedar River, referred to as the Cedar-Sammamish Watershed Basin, or Water Resource Inventory Area (WRIA) 8. Lake Washington's two major influent rivers are the Cedar and Sammamish Rivers. The Cedar River, which enters at the southern end, contributes about 57% (611 million cubic meters [m^3] per year) of the annual hydraulic load (water inflow per year) and 25% (10,100 kilograms [kg] per year) of the phosphorus (P) load (amount of the nutrient phosphorus that is delivered to the lake per year). Water from Lake Sammamish via the Sammamish River, which enters the lake from the north, contributes 27% (287 million m^3 per year) of the hydraulic load and 41% (16,400 kg per year) of the P load. The majority of the immediate watershed is highly developed, with 63% of the watershed fully developed (King County Lakes Monitoring Program, 2002). The headwaters of the Cedar River are in a protected watershed owned by the Seattle Water Department.

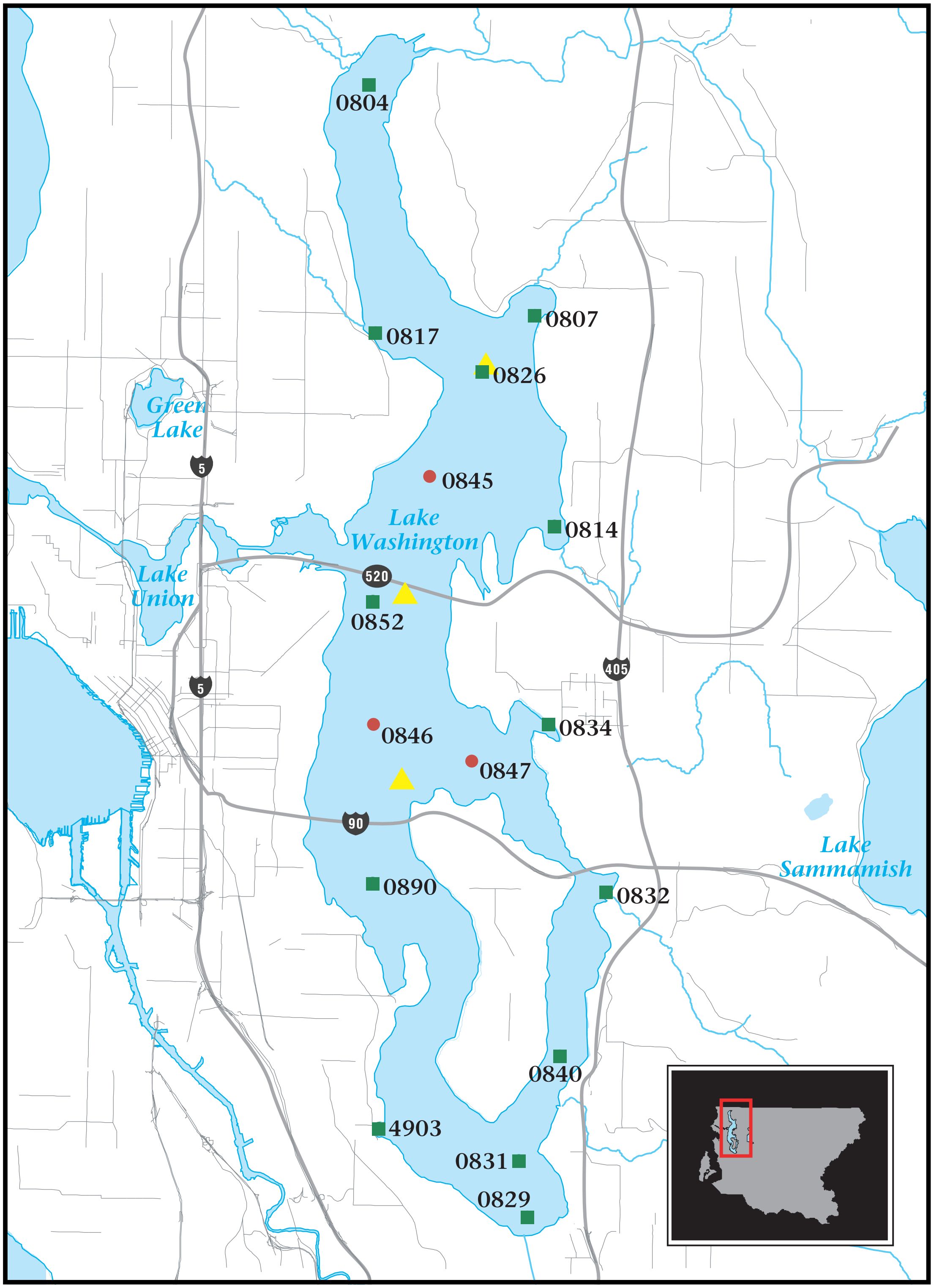

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Figure 1

Location of Lake Washington Water Sample Stations

- Additional Low Level Metals Stations
- Lakes Monitoring Stations
- R.U.S.S. Buoy
- Streams
- Major Roads

King County
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The basin of Lake Washington is a deep, narrow, glacial trough with steeply sloping sides, sculpted by the Vashon ice sheet, the last continental glacier to move through the Seattle area. The lake drains to Puget Sound and lies 6.3 m above sea level at mean lower low tide. The water passes through Lake Union and the Lake Washington Ship Canal, which was constructed in 1916 and is the only outlet from Lakes Sammamish and Washington. Prior to construction of the canal, the principal inflow was from the Sammamish River at the north end of Lake Washington, and the outflow was through the Black River at the south end of the lake (Chrzastowski, 1983). Construction of the canal resulted in the lowering of the lake 3 m to its present level, blocking off the Black River by diverting the Cedar River into Lake Washington. Mercer Island lies in the southern half of the lake, and is separated from the east shore by a relatively shallow and narrow channel, and from the west shore by a much wider and deeper channel (Chrzastowski, 1983; King County Lakes Monitoring Program, 2002). The physical characteristics of Lake Washington and its drainage basin are summarized in Table 1.

Table 1.
Physical Characteristics of Lake Washington[a]

Characteristic	English Units	Metric Units
Drainage Area	300,000 acres	1,274 km^2
Lake Area	21,500 acres	87.6 km^2
Lake Volume	2,350,000 acre-ft	2.9x10^9 m^3
Mean Depth	108 ft	32.9 m
Maximum Depth	214 ft	65.2 m
Flushing Rate	0.43 per year[b]	
Depth of the Epilimnion	33 ft	12 m
Epilimnion:Hypolimnion Ratio	0.387	
Length	13 miles	21 km
Main Inflows	Cedar River (57% of total volume) Sammamish River (27% of total volume)	
Main Outlet	Ship Canal to Puget Sound	
Typical Period of Stratification	Late March to Early December	
Trophic State	Mesotrophic	

[a] King County Lakes Monitoring Program, 2002

[b] Water renewal rate, or flushing rate, is the fraction of the lake's volume replaced per year.

Lake Washington is a monomictic (having one mixing and one stratification event per year), isothermal lake that undergoes complete mixing from the surface to bottom during December through March. In April, the lake begins to stratify, and by June the lake is strongly stratified and remains so until October. At this time the surface water cools and stratification of the lake starts to weaken until the thermal stratification that physically separates the surface waters (epilimnion) from the deeper waters (hypolimnion) breaks down, allowing the entire water column to mix.

The lake received increasing amounts of secondary treated sewage between 1941 and 1963, which resulted in increased nutrient enrichment (eutrophication) and declining water quality. From 1955 to 1973, the lake's algae were dominated by cyanobacteria, which can be severe bloom-forming nuisances. Cyanobacteria (formerly known as blue-green algae) are bacteria, not true algae, but they can photosynthesize and ecologically function similar to algae. Sewage effluent was completely diverted from the lake during 1963 and 1967, except for infrequent untreated combined sewer overflows (CSOs) (King County Wastewater Treatment Division, 2001). Rapid and predicted water quality improvements followed diversion with dramatically decreased algae abundance, especially the cyanobacteria, and associated increased transparency. The lake's eutrophication was thoroughly documented by W.T. Edmondson and associates at the University of Washington (Edmondson et al., 1956; Edmondson and Lehman, 1981; Edmondson, 1994).

1.3. Sampling Stations

Sixteen water quality sampling stations are monitored in Lake Washington (Figure 2). Five routine water quality sampling stations and three additional stations for monitoring metals are located in the deep, open waters of the lake. These deep stations are referred to as pelagic stations and have maximum sampling depths ranging from 25 to 60 m. Changes in water quality observed over time at these sites reflect broad, large-scale, and small-scale landscape changes in the watershed. Eight water quality sampling stations are distributed along the shoreline of the lake, primarily off the mouths of influent streams. These stations are referred to as the nearshore stations and have maximum sampling depths ranging from 1 to 9 m. Changes in water quality at the nearshore stations are more directly influenced by shoreline activities and by the quality and quantity of inflowing stream water than are the pelagic stations. Changes at nearshore sites often occur more quickly and are often greater than those observed in the middle of the lake. The locations of the sixteen stations, sample depths, and the analytes monitored at each are summarized in Table 2.

Station 4903 was established to document water quality impacts from the Henderson Street CSO to Lake Washington. The Henderson CSO is the last uncontrolled CSO in Lake Washington and is scheduled to be controlled by 2005. Annual means calculated for Station 4903 for water quality constituents were not statistically different from the other nearshore stations, and therefore are not discussed further in the text.

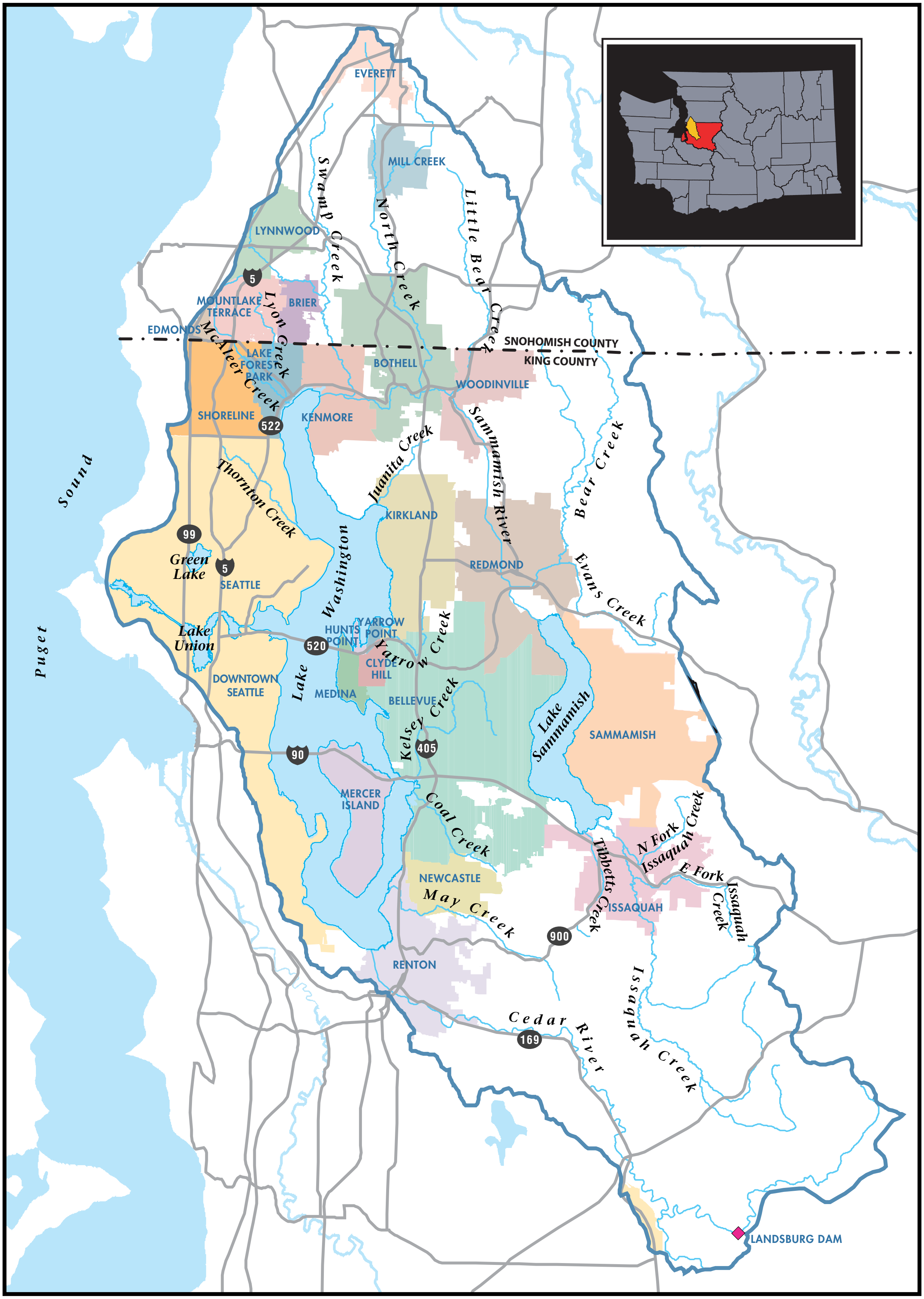

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Figure 2

SWAMP Study Area

- Streams
- Major Roads
- Study Area Boundary
- Lakes

King County

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Table 2.
Water Quality Sampling Stations in Lake Washington

Locator Number	Description of Sampling Site (Influent Stream in Parentheses for Nearshore Stations)	Type of Station	Depth (m)	Primary Sampling Depths (m)	Number of Organics Samples Collected	Number of Metals Samples Collected	Conventionals Sampled
0804	North end, mid-bay	Nearshore	8	1, 3, 8	1	19	Yes
0807	Juanita Bay, mid-bay	Nearshore	3	1, 3	16	17	Yes
0814	Yarrow Bay, south end	Nearshore	7	1, 7	1	18	Yes
0817	Matthews Beach, near Thornton Creek	Nearshore	3	1, 3	16	19	Yes
0826	Mid-lake north, off Sand Point	Pelagic	47	1, 5, 10, 15, 20, 25, 30, 40, 47	16	40	Yes
0829	South end, near Boeing ramp	Nearshore	9	1, 9	1	19	Yes
0831	Mid-lake south	Pelagic	25	1, 5, 10, 15, 20, 25	17	38	Yes
0832	Newport Yacht Basin, near Coal Creek	Nearshore	1	1	1	9	Yes
0834	Meydenbauer Bay, near Meydenbauer Park	Nearshore	7	1, 7	17	17	Yes
0840	East Mercer Island channel	Pelagic	25	1, 5, 10, 15, 20, 25	16	18	Yes
0845	Lake Washington, off Wolf Bay, in open water	Pelagic	59	1, 57, 58, 59	0	25	No
0846	Lake Washington, off Madrona Park, in open water	Pelagic	58	1, 53, 56, 57, 58, 59, 64	0	24	No

Table 2.
Water Quality Sampling Stations in Lake Washington (Continued)

Locator Number	Description of Sampling Site (Influent Stream in Parentheses for Nearshore Stations)	Type of Station	Depth (m)	Primary Sampling Depths (m)	Number of Organics Samples Collected	Number of Metals Samples Collected	Conventionals Sampled
0847	Lake Washington, off Chism Park, NE of Calkins Point (Mercer Island)	Pelagic	45	1, 42, 44, 45, 46, 47	0	22	No
0852	Madison Park	Pelagic	60	1, 5, 10, 15, 20, 25, 30, 40, 50, 55, 60	15	41	Yes
0890	South of I-90, south-central basin	Pelagic	47	1, 5, 10, 15, 20, 25, 30, 40, 45	16	40	Yes
4903	CSO - Lake Washington, combined sewer overflow at Henderson St.	Nearshore	1	1	4	11	Yes

Source: King County Lakes Monitoring Program, 2002

2. HISTORICAL WATER COLUMN CONDITIONS

2.1. Response to Wastewater Diversion

The recovery of Lake Washington following wastewater diversion is one of the most celebrated and dramatic cases in the world (Cullen and Forsberg, 1988; Edmonson, 1991; Cooke et al., 1993). These are appropriate terms to describe the lake's recovery, because at the time of the diversion (in the 1960s), there was much doubt in the scientific community whether recovery from a eutrophic state was even possible. Two principal reasons for the recovery's fame are:

1. The long-term data record, which documented the following:
    - The lake's transition to a eutrophic, over-enriched state in the early 1950s (Edmondson et al., 1956; Edmondson, 1994).
    - The lake's recovery following diversion of 88% of the phosphorus loading from 1963 to 1967 (Edmondson, 1970, 1978; Edmondson and Lehman, 1981).
2. The rapid recovery from a pre-diversion, whole-lake TP concentration of 64 µg/L, which was illustrated by the following;
    - An equilibrium level of about 20 µg/L was reached by 1970 (Figure 3); the winter mean for 1969 through 1975 was 19 µg/L.
    - The equilibrium was reached only 3 years after diversion was completed.
    - The TP concentration reached 90% of the equilibrium level in just over 2 years.

The January whole-lake TP concentration remained stable from the remainder of the 1970s, with a 4-year (1976 through 1979) mean of 17 µg/L (Figure 3). January or January-March means were used in past work on Lake Washington because the lake was well mixed and P concentrations were highest during that time of year (Edmondson, 1994). As will be discussed in Section 4.2.5.1, January volume-weighted, whole-lake TP has continued to average 15 µg/L from 1990 through 2001. That level is similar to the summer mean surface water concentration, which has averaged 16 µg/L from 1990 through 2001.

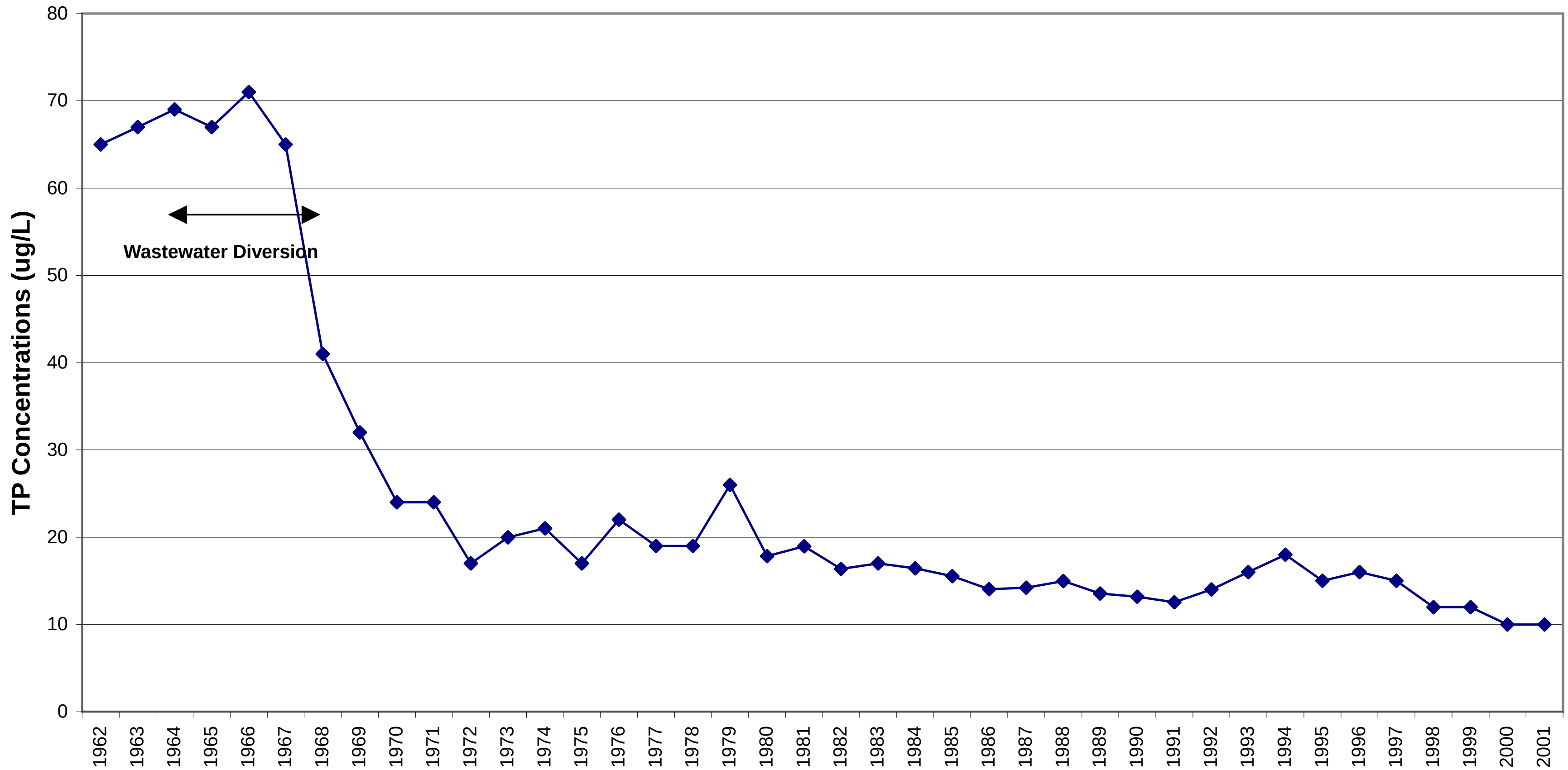

Figure 3. Changes in Whole-Lake Total Phosphorus Concentrations from January 1, 1962 to1979 in Lake Washington Before, During, and After Diversion of Secondary Treated Wastewater (modified from Edmondson and Lehman, 1981)

Several factors contributed to Lake Washington's prompt recovery to a lower equilibrium phosphorus concentration following its decreased phosphorus input. These factors include the lake's (1) relatively fast water renewal rate (~ 0.4/year); (2) depth (64 m maximum, 37 m mean); (3) aerobic hypolimnion with a relatively small epilimnion:hypolimnion ratio; and (4) relatively short period of enrichment. Water renewal rate, or flushing rate, is the fraction of the lake's volume replaced per year. In this case, a water renewal rate of 0.4 times per year means that the whole water volume of Lake Washington is theoretically replaced in 2.5 years. So, in effect, the residual, high nutrient-laden lake water was quickly diluted by, or replaced with, low nutrient inflow water supplied in large part by the Cedar River, which contains a volume-weighted inflow concentration of only 17.2 µg/L (see Section 4.5.2.1).

The relatively deep character of the lake allows strong thermal stratification, which separates the surface (epilimnion) and bottom (hypolimnion). Strong stratification reduces nutrient availability for algae in the well-lighted epilimnion; nutrients that sink from the epilimnion during summer are not effectively returned to that layer. Also, the large hypolimnetic volume and short period of historic enrichment combined to prevent an anoxic condition (zero oxygen at the sediment-water surface) from developing, which would have allowed the increased content of sediment phosphorus to recycle to the water column. That process, known as internal loading, would have prolonged the recovery. Other lakes have responded to diversion of a large fraction of phosphorus input, but not to such a low equilibrium level or as quickly as observed in Lake Washington. Such slow response in most other lakes was primarily due to continued recycling from sediment, or internal loading (Cullen and Forsberg, 1988; Cooke et al., 1993; Welch and Cooke, 1993; Sondergaard et al., 2001).

Chlorophyll *a* (chl *a*), which is the green pigment in photosynthetic plants and is used universally as an index of algal biomass, decreased from a pre-diversion summer mean of 36 µg/L to a post-diversion mean of 6 µg/L, in proportion to the decrease in P. Transparency, which is a highly reliable measure of water clarity, increased from 1.0 m to 3.1 m, in proportion to the decrease in chl *a* (Edmondson and Lehman, 1981).

Changes in nitrogen (N) concentrations relative to P concentrations during eutrophication and recovery were also of interest. Before diversion, the N:P ratio in Lake Washington had declined to the point of N being more limiting to algae growth than P (i.e., N:P was less than 10:1). However, with the removal of sewage effluent (which has a low N:P ratio of ~ 3:1), the lake's N:P ratio increased to over 20:1, and P once again limited algae. These results from Lake Washington were instrumental in convincing the scientific community that P, not N or carbon, was the nutrient primarily responsible for the effects of eutrophication in freshwater (Edmondson, 1970).

The improvement in the lake's quality did not end with marked decreases in P and chl *a* and increase in transparency, but went through a biological transition starting with the recurrence of *Daphnia,* a zooplankton that eats algae (Edmondson and Litt, 1982). *Daphnia* returned in abundance in 1976 due to a prior decrease in one of its predators, *Neomysis*, a large crustacean (Murtaugh, 1981), and the filamentous cyanobacteria *Oscillatoria* that interfered with *Daphnia* filter feeding (Infante and Abella, 1985). As a result of a shift to more edible algae and reduced predation in the late 1970s, increased grazing by *Daphnia* on algae decreased chl *a* by 50% to 3 µg/L as a 4-year summer mean. Summer average transparency more than doubled to 7 m, with maximums ranging from 4.5 to 10.0 m, due to the algae reduction (Edmondson and Litt, 1982). Transparency continued to remain high into the 1980s, averaging 6.4 m from 1976 to 1985, while *Daphnia* remained abundant at about 10 animals/L (Edmondson, 1988).

Summer (June through September) chl *a* concentration, determined by King County, has remained at about the same low level from 1993 to 2001, averaging 2.7 µg/L. Transparency determined by King County during that 9-year period at the deep station (0852) ranged from 3.5 to 5.6 m, with a mean of 4.5 m. However, transparency determined at the deep station by University of Washington personnel during 1989 to 2001 was similar to that during the late 1970s and early 1980s, with a range of 5.1 to 7.8 m and overall mean of 7.1 m. The 7.0-m mean (4.5- to 10.0-m range) transparency reported by Edmondson and Litt (1982) from 1976 to 1979 is higher than expected from the trophic state equations using a chl *a* concentration of 3.1 µg/L as the basis for estimating transparency. This equation developed by Carlson (1977), which includes Lake Washington data, predicts a transparency of 3.6 m from a chl *a* of 3.1 µg/L. Other factors that might explain the difference between King County and University of Washington measured transparency will be discussed later in Section 4.1.2.

The algal species composition also changed dramatically during the periods of eutrophication and recovery. The typical nuisance cyanobacteria, represented by *Aphanizomenon* and *Anabaena*, had occurred during the early 1950s. The cyanobacteria *Oscillatoria*, which does not form floating mats, was first evident in great abundance in 1955 (Edmondson et al., 1956). When *Oscillatoria* largely disappeared, nearly 10 years after diversion, these nuisance taxa (especially *Aphanizomenon*) became relatively more abundant. However, *Aphanizomenon* and *Anabaena* have not reached the high level that *Oscillatoria* attained prior to diversion (Edmondson, 1994), due to the limiting low levels of P that exist today. These nuisance taxa have continued to be dominant members of the algae community during the 1990 through 2001 period.

The lake's response to increasing then decreasing enrichment was also reflected in the profundal (deep bottom) sediments (Shapiro et al., 1971). TP content in the sediments increased to around 6 mg/g from a background of 1 to 2 mg/g, which is typical of lakes in the area. By 1972, sediment TP content had decreased, but had not yet returned to background levels (Edmondson, 1994). Recent analysis of deep bottom sediments by King County from 1995 to 2002 showed a mean TP concentration of 0.745 mg/g (Coughlin, 2002 personal communication).

Hypolimnetic dissolved oxygen (DO) also decreased with increasing enrichment; DO declined due to the increased demand by sinking organic matter produced from increased enrichment. The areal hypolimnetic oxygen deficit rate (AHOD), which is a seasonal measure of that oxygen demand (see Section 4.2.1 for calculation), had reached a level of 810 mg/m^2-day in 1964. Pre-enrichment AHOD values are not available, but were probably much lower, because by 1974, AHOD had declined to 580 mg/m^2-day (Welch and Perkins, 1979b). The AHOD from 1993 to 2001 averaged 473 mg/ m^2-day. For perspective, a rate of 550 mg/m^2-day is often considered indicative of a eutrophic state (Mortimer, 1941).

Had Lake Washington's hypolimnion been smaller, anoxia would probably have resulted, with high rates of P internal loading, from the increased sediment P concentration. High AHOD rates (530 to 650 mg/m^2-day) do exist in shallow western Washington lakes that develop anoxic hypolimnia, such as Pine, Meridian, and Sammamish, with mean depths of 6, 12.5, and 18 m, respectively (Welch and Perkins, 1979). The fact that the hypolimnion of Lake Washington (mean depth 37 m) did not reach an anoxic state illustrates the importance of depth in the lake's quick recovery from nutrient enrichment; the oxygen reserve in the large hypolimnetic water volume exceeded the demand from increased organic matter.

Another significant historical change in Lake Washington has been in alkalinity, which is a measure of buffering capacity and is essentially $Ca(HCO_3)_2$ at the pH range in the lake. Alkalinity has increased by one third over a 35-year period, from about 0.6 meq/L to about 0.8 meq/L (30 to 40 mg/L as $CaCO_3$). That change was hypothesized to be a result of soil disturbance due to increased development within the watershed (Edmondson, 1994). The result was increased leaching of $Ca(HCO_3)_2$ from the exposed soil, resulting in higher alkalinity in the lake.

2.2. Comparison with Other Area Lakes

While Lake Washington reached a eutrophic state in the early 1960s from direct inputs of wastewater from ten wastewater treatment plants, it nonetheless recovered rapidly to a mesotrophic state that exists today. The key to such a rapid and complete recovery was the lake's depth, which prevented anoxia from developing in the hypolimnion. The lake's relatively fast flushing rate accelerated recovery. The lake's shape, depth, and oxic condition allowed for a high rate of retention (average 61%) of incoming TP by the sediments, which was maintained throughout the recovery period (Edmondson and Lehman, 1981). Lakes with high internal loading usually have negative retention for many years following reduction in external input (Sondergaard et al., 2001). If Lake Washington had half the hypolimnetic volume, anoxia would have occurred within the stratified period (see calculation in Section 4.2.1), yielding high P internal loading rates from the P-enriched sediment. As observed in Lake Washington, mean hypolimnetic DO remained above 4 mg/L throughout the stratified period in 1957 (Edmondson, 1966). Minimum hypolimnetic DO remained above 2.5 mg/L from 1990 to 2001. The nominal, off-bottom DO level below which phosphorus recycling is likely to occur is often cited as 1.0 mg/L (Nurnberg, 1995).

By way of comparison, P internal loading during summer was found to be more important than external loading (68 $\pm$ 21% of total) in 14 of 17 lakes examined from western Washington (Welch and Jacoby, 2001). Six of these 14 lakes stratify, and all are more shallow than Lake Washington. None has received wastewater in the past, and surficial sediment TP content was typically 1 to 2 mg/g, only 15 to 30% of the maximum concentration reached in Lake Washington sediment (Shapiro et al., 1971). Internal loading was important, even in unstratified lakes with no prolonged anoxia. The greater importance of internal than external loading during summer was due to the generally dry summer with low water input. Therefore, internal loading may also have been relatively important in Lake Washington had it been shallow enough to reach anoxia.

The importance of internal loading in many western Washington lakes would have been greater with higher external loading. Some of the lakes analyzed by Welch and Jacoby (2001) were in watersheds undergoing development, but none have had the high external loading from wastewater near what was the maximum input to Lake Washington (1.1 g TP/m^2-yr). With such high external loading to these shallower lakes, sediment TP content would have increased and the role of internal loading would have undoubtedly become even more important than indicated above, potentially prolonging recovery from any reduction in external load. Greatly prolonged recovery has been the case for most lakes in the world responding to wastewater diversion (Sondergaard et al., 2001).

Comparison of Lake Washington with other western Washington lakes illustrates that depth and the relatively short period of enrichment were instrumental in accounting for the rapid recovery of Lake Washington. However, that does not mean Lake Washington is insensitive to changes in phosphorus loading. Rather, the record of response through changes in algal abundance, algal species composition, zooplankton composition, and transparency is clear evidence of its sensitivity to increased and decreased phosphorus loading.

3. WATER COLUMN MONITORING BACKGROUND

Water column monitoring by King County is designed to account for natural seasonal changes in the water column as well as changes from anthropogenic (human) input. General water quality parameters (temperature, transparency, DO, conductivity, alkalinity, P, N, and chl *a*) are monitored at multiple depths. Below is a more detailed discussion of the water quality parameters sampled in Lake Washington.

3.1. Description of Water Quality Parameters

3.1.1. Temperature

Water temperature is an important water quality variable because it (1) directly affects biological and chemical activity, (2) affects water density, which determines water column stability, and (3) defines available habitat for a variety of aquatic species.

The seasonal pattern of temperature throughout the water column is determined largely by climatic factors. During winter, as in other temperate, monomictic lakes, temperature throughout the water column is relatively constant, because the lake is well mixed. The water column becomes stratified into a warm, less dense surface layer (or epilimnion), an intermediate metalimnion, and a colder, denser hypolimnion during summer. This stratified condition develops as increased solar radiation in the spring heats the surface water. The depth of mixing defines the bottom of the epilimnion and occurs where the wind energy exerted to mix the water column equals the energy of resistance due to the higher density. Because the epilimnion and hypolimnion do not mix during the summer-stratified period, chemical characteristics in the two layers may become quite different. In the fall, as the surface water cools and becomes more dense and windy conditions become more prevalent, thermal stratification begins to breakdown and relatively complete mixing eventually resumes.

3.1.2. Transparency

Water transparency, or clarity, was measured with a standard black-and-white metal Secchi disk that is 28 cm in diameter. The depth at which the disk disappears from sight is determined by attenuation of light penetrating through the water column. Light attenuation through the water column is influenced by several factors, including living plankton algae, non-algal turbidity from suspended sediment and organic detritus, and color. Therefore, the depth that the disk disappears decreases as the concentration of particles and the light they scatter and absorb increases.

Transparency of most lakes is dependent largely on the concentration of algal particles, especially in summer, which is usually the season used to indicate the state of lake quality and trophic state. Chlorophyll *a*, as an index of algal biomass, is inversely related to Secchi transparency (Carlson, 1977). As noted in Section 2.1, Lake Washington data were used to develop the Carlson trophic state index, so transparency in this large lake is primarily dependent on the concentration of living algae, especially during summer.

3.1.3. Dissolved Oxygen

Dissolved oxygen (DO) is an important constituent that directly affects, and is affected by, abundance and diversity of aquatic organisms. Vertebrate and invertebrate taxa have specific tolerances to low DO for metabolic needs. Water quality criteria for DO are often established to protect the reproduction and growth of sensitive species. Water bodies with DO near saturation levels (e.g., 9 mg/L at 20ºC) at all depths are capable of sustaining a diverse assemblage of aquatic organisms. As DO declines near the sediment surface, species more tolerant of low DO replace those that are less tolerant.

During summer stratification, DO concentrations may change dramatically with depth to the point of total depletion near the bottom sediments or even throughout the hypolimnion. DO is produced through photosynthesis and consumed through respiration in the epilimnion, but substantial depletion normally does not occur due to atmospheric reaeration, except possibly during the decline of large algal blooms or in dense, localized macrophyte beds. However, consumption can easily exceed supply in the hypolimnion, where photosynthesis and atmospheric reaeration are largely absent and settled organic matter is abundant.

The magnitude of the loss of DO in the hypolimnion is somewhat proportional to surface water algal production. Thus, the level of DO and the rate of its loss are used as an index of eutrophication or trophic state. As discussed in Section 2.1, a measure of DO depletion rate is the AHOD, which is the daily rate of DO loss per unit area of the hypolimnion.

3.1.4. Conductivity

Specific conductance (conductivity) is a measure of the capacity of water to conduct an electric current standardized to that capacity at 25 ^{o}C so comparisons can be made among waters of different temperatures. Temperature and the concentration of dissolved ions in water determines the conductivity of water. Because of the local predominantly igneous rock geology, water in the Puget Sound region generally has low levels of dissolved minerals and relatively low conductivity. In King County streams and lakes, conductivity generally averages less than 100 μmhos/cm during base flows (King County, 1996). Active land use and land-use conversion from open space to developed areas tend to increase conductivity, and increases indicate the presence of dissolved ions potentially from a pollutant source (e.g., nitrite-nitrate from fertilizers) (King County Lake Monitoring Program, 2002) or soil disturbance exposing potential dissolvable ions to storm water.

3.1.5. Alkalinity

Alkalinity of water refers to the presence of compounds that buffer changes in lake pH. Alkalinity in most lakes is imparted by the presence of bicarbonates, carbonates, and hydroxides, and is expressed in mg $CaCO_3$/L (Wetzel, 1983). Alkalinity of surface waters in western Washington is generally low due to the lack of sedimentary carbonate in the watersheds (Carroll and Pelletier, 1991). The pH in poorly buffered water often increases to high levels (> 10) during intense algal blooms when photosynthetic removal of CO_2 by algae is faster than replenishment from the atmosphere.

3.1.6. pH

Hydrogen ion activity in water is measured as the negative log of the hydrogen ion concentration (pH) and indicates the acidity of a lake; a pH of 7.0 is neutral. Because pH is inversely related to hydrogen ion activity, waters with a pH above 7.0 are alkaline and those with a pH below 7.0 are acidic. As discussed above, photosynthesis removes carbon (in the form of carbonic acid and bicarbonate) from the water and reduces the concentration of hydrogen ions, increasing pH levels. For this reason, pH is often higher at the surface during daylight hours in the summer, especially in low-buffered waters. Dense, rooted aquatic macrophyte communities can also increase pH during intense photosynthetic periods. Frodge et al. (1990) observed pHs greater than 10 in dense beds of milfoil in Lake Washington. Diffusion of CO_2 from the atmosphere, respiration, and decomposition lower the pH. Organic matter that settles onto the bottom of the lake and is decomposed contributes to differences in pH readings with depth in the lake. Water near the bottom and in surficial sediments usually has a pH around 6 due to bacterial decomposition of settled organic matter. However, most surface waters have a pH between 7.0 and 8.5, which is slightly alkaline. High-elevation lakes in the Cascade Mountains often have a pH below 7.0 due to poor buffering capacity and are therefore highly sensitive to acid precipitation.

3.1.7. Phosphorus

Phosphorus is an essential element for the metabolic processes of both plants and animals. It occurs naturally in soil and rock and can be found in plant and animal tissue as well as on particles in the atmosphere. Total phosphorus (TP) represents both organic and inorganic P in particulate and dissolved forms. Soluble reactive phosphorus (SRP) generally represents that portion of P (largely phosphate) that is dissolved in water and is readily available for biological uptake.

Phosphorus is important to algal growth and has historically been the nutrient most closely linked to the historical change in algal production in Lake Washington (see Sections 2.1 and 3.1.9). Because Lake Washington is P limited (see Section 3.1.9), increased availability of P could lead to increased algal blooms. Specifically, human activities within the watershed and direct discharge of treated sewage effluent increases the amount of P entering a lake and is often the cause of serious water quality degradation.

3.1.8. Nitrogen

Nitrogen exists in several forms in aquatic systems, including nitrite-nitrogen, nitrate-nitrogen, ammonium-nitrogen, organic nitrogen, and elemental nitrogen. Aquatic organisms commonly use the dissolved forms of nitrogen, ammonium-nitrogen, and nitrate-nitrogen. Total nitrogen (TN), nitrate plus nitrite, and ammonium-nitrogen were the forms of N historically sampled in Lake Washington. Although nitrate and nitrite nitrogen are often reported as one parameter, nitrate-nitrite nitrogen, this report refers to this parameter as nitrate-nitrogen due to environmental conditions in Lake Washington, which result in low nitrite concentrations. Lake Washington tends to be a P-limited system, therefore a small increase in nitrogen inputs would have little effect on the productivity of the lake (see Section 3.1.9). However, long-term changes in nitrogen to phosphorus ratios may forecast changes in phytoplankton community composition [e.g., Downing et al. (2001) Predicting cyanobacteria dominance in lakes. Can. J. Fish. Aquat. Sci. 58:1905-1908]. Also, long-term tracking of nitrogen may provide an understanding of some of the impacts of watershed activity on the lake. Input of N could affect water quality in Puget Sound, which is N limited.

3.1.9. Nutrient Limitation

Lake water quality problems are most often associated with an overabundance of nutrients, which can result in proportionately higher production of algae. Determining the limiting nutrient is important for controlling algal abundance and managing water quality problems. The limiting nutrient in lakes is typically N or P. In oligotrophic lakes with low productivity, P tends to be the nutrient in shortest supply and therefore the most limiting factor relative to algal production. As lakes become more enriched with P, relative to N, limitation tends to shift to N, as was the case in Lake Washington during the 1950s and 1960s (see Section 2.1). However, with the diversion of sewage effluent (and the resulting low N:P ratio), Lake Washington has returned to a P-limited system.

Nutrient ratios are usually expressed on a weight (mass) basis, e.g., µg TN:µg TP. Generally, if the TN to TP ratio (TN:TP) is greater than 16:1 (by weight) then the growth of algae in the lake is limited by P (Carroll and Pelletier, 1991). TN:TP ratios less than 5:1 (by weight) generally indicate that N is the limiting nutrient. Intermediate ratios indicate either nutrient may be limiting. The N:P ratio tends to indicate which nutrient is most limiting growth in the short term; however, algal biomass is usually linked most closely with TP regardless of the N:P ratio. This is true because N limitation favors N-fixing species, which are all cyanobacteria and are ultimately dependent on P. Hence, TP is the nutrient that is emphasized to manage lake quality (Welch, 1992). The Redfield TN:TP ratio of 16:1, calculated using the number of atoms, is approximately equivalent to 7:1 by weight.

Generally, if the molecular TN:TP ratio is greater than 16:1, then the algal productivity is considered limited by P availability (Carroll and Pelletier, 1991). Nutrient ratios are usually expressed on a weight (mass) basis, e.g., µg TN:µg TP. The Redfield TN:TP ratio of 16:1, calculated using the number of atoms, is approximately equivalent to 7:1 by weight.

3.1.10. Algae (Chlorophyll *a*)

Chlorophyll *a* is the photosynthetic pigment present in all algae and cyanobacteria. Chl *a* is used by these organisms in the process of photosynthesis, which converts light energy, carbon dioxide, and water to chemical energy stored in sugar. The ratio of algal biomass, or carbon, to chl *a* varies with species, nutrient availability, and environmental conditions. Thus chl *a* is not an exact measurement of algal biomass. Nevertheless, it is used universally as an indicator of algal biomass and lake trophic state.

3.1.11. Metals

Many metals naturally occur in surface waters, originating from the erosion of watershed soils, groundwater discharge, and atmospheric deposition (e.g., from windblown dusts, volcanogenic particles, and forest fires). Anthropogenic sources of metals to Lake Washington have included wastewater effluent, storm water, groundwater, atmospheric deposition, and boats. The fate of metals in the environment and resulting concentrations in lake water vary with solubility, biding affinity and sorption to particles, complexation with organic matter, sorption and desorption, biological uptake, and other chemical and biochemical properties and processes (Moore and Ramamoorthy, 1984a).

Many metals are important micronutrients for humans and other animals. However, elevated concentrations of certain metals may cause toxic effects to people, wildlife, fish, or other aquatic life (Moore and Ramamoorthy, 1984a). For example, lead is well known as a neurotoxin and is associated with skin disease and cancer (USEPA, 2002). At elevated concentrations, copper is toxic to most aquatic plants, algae, and many freshwater fish and invertebrate species. Although concentrations of metals associated with toxic effects have been reported in storm water and some urban streams of western Washington, metals toxicity has generally not been observed in regional lake water (MacCoy and Black, 1998).

The toxicity of many potentially harmful metals increases when the hardness or pH of the water decreases. Water hardness is primarily dependent on the concentration of calcium and magnesium carbonates. Metal ions can form insoluble precipitates with these carbonates, reducing the metal's availability for uptake by the organism (Blowers, 2002). The carbonates with which metals bind are alkaline, and a decrease in the ambient pH can dissolve the metal-carbonate precipitates or interfere with the metal's association with other lignins. This results in a greater proportion of the metal occurring in its ionized form, making it more available for ingestion or uptake by aquatic organisms. While both water hardness and pH can affect metal toxicity, water quality standards address only the effect of hardness on metal toxicity.

3.1.12. Organic Compounds

Organic compounds are carbon-based molecules; some examples include pesticides, volatile and semi-volatile chemicals, and polycyclic aromatic hydrocarbons (PAHs). Many of these chemicals persist in the aquatic environment long after their initial use (e.g., DDT and metabolites). Similar to metals, organic compounds also enter surface waters from natural and anthropogenic sources (e.g., coal combustion, forest fires). Organic compounds enter surface waters from municipal and industrial effluents, storm water, pesticide applications, leaks and spills, contaminated groundwater, seepage from older uncontrolled landfills and contaminated soils, and atmospheric deposition. Lake-water concentrations are determined by inputs from these sources and the fate and transport processes, such as sorption-desorption processes, volatilization, and chemical and biological transformations (Moore and Ramamoorthy, 1984b). As with all chemicals, when present in sufficiently high concentrations, exposure to toxic levels of organic compounds may cause adverse effects to people, wildlife, fish, or other aquatic life. Organic compounds have been frequently detected in water and sediments of urban streams, lakes, and estuaries of western Washington (i.e., PAHs and certain phthalate esters) (Bortleson and Davis, 1997; MacCoy and Black, 1998). However, there is a lack of data regarding organic chemical contamination and subsequent toxicity within lake waters of this region.

Recently, a number of organic compounds classified as "endocrine disrupters" have become a cause for concern. The U.S. Environmental Protection Agency (USEPA) defines endocrine-disrupting chemicals as substances that interfere with the production, release, transport, metabolism, binding, action, or elimination of natural hormones in an organism that are responsible for the maintenance of homeostasis and regulation of developmental processes. Current research suggests that wastewater effluent may be a potential source of endocrine-disrupting chemicals to the environment. King County is currently in the process of beginning to monitor some of these chemicals in ambient water.

3.2. Water Column Sampling Methods

The Major Lakes Monitoring Program was designed to monitor long-term trends and seasonal water quality in Lakes Washington, Sammamish, and Union. These changes are accounted for by monthly and bimonthly sampling at all stations. Rainfall patterns, changes in sunlight intensity, and day length all combine to generate seasonal cycles in the lake. These seasonal water quality cycles are not uniform at all depths in the lake, so at each station samples are collected from 1 m below the surface of the lake to just above the lake bottom.

3.2.1. Field Methods

Grab (instantaneous) samples for alkalinity, nutrients, and chl *a* were collected at various depths in the water column using Vandorn bottles at the shallow stations and Niskin bottles at the deeper, open water stations. Bacteria samples were also collected, primarily at the surface of the lake, but also periodically at depth. Variables measured in the field (pH, temperature, DO, and conductivity) were measured using a Hydrolab probe lowered to various depths at each station. Secchi depths were measured at each station using a 28-cm-diameter black-and-white Secchi disk.

3.2.2. Laboratory Methods

With the exception of field measurements, water column variables were analyzed at the King County Environmental Laboratory (KCEL). Laboratory methods and detection limits are provided in Table 3. Additional information about the KCEL can be obtained at the laboratory's website [http://dnr.metrokc.gov/wlr /envlab/index.htm].

All samples were analyzed within their respective holding times, and quality assurance/quality control procedures included the use of blanks, duplicates, and spikes where appropriate. All data were reviewed before entry into the Laboratory Information Management System (LIMS) database.

Table 3.
Laboratory Methods and Detection Limits for Water Samples[a]

Parameter	Standard Methods	MDL* (mg/L)	RDL** (mg/L)
Alkalinity	SM 2320-B	0.2	1
Chlorophyll *a*	SM 10200-H	0.01 mg/m^3	0.05 mg/m^3
Ammonia-Nitrogen	SM 4500-NH3-H	0.02	0.04
Total Nitrogen	SM4500-N-D + SM4500-NO3-F	0.05	0.1
Nitrate/Nitrite	SM4500-NO3-F	0.05	0.1
Soluble Reactive Phosphorus	SM 4500-P-F	0.002	0.05
Total Phosphorus	SM 4500-P-B,E	0.005	0.01
Turbidity	SM 2130-B	0.5 NTU	2 NTU

a Taken from King County Environmental Laboratory, 2002
* Method Detection Limit
** Reporting Detection Limit

4. SUMMARY OF 1990 TO 2001 MONITORING DATA

This section summarizes the monitoring data and discusses their significance to provide the reader with a descriptive perspective of the condition of Lake Washington. Specifically, the water quality data were analyzed with the following objectives:

- To characterize the current status of the lake relative to accepted ecological indicators, such as transparency, DO, TP, and chl *a*.
- To identify water quality trends during the study period, with reference to historical conditions where applicable.
- To identify water quality differences between nearshore and pelagic areas of the lake.
- To provide information to be used in making future environmental management decisions that may impact the lake.

All data were assessed to define vertical and horizontal differences by first examining each parameter by station and depth, then grouping the stations by nearshore and pelagic regions of the lake. To characterize the lake as a whole, volume-weighted averages (averages that take into account the specific volume of water that a sample represents) were calculated where data were available. Whole-lake, nearshore, pelagic, epilimnion (0 to 20 m), and hypolimnion (25 to 60 m) volume-weighted averages were calculated for P and N parameters. See Appendix A for tables summarizing annual means and standard deviations for all stations and parameters.

Monthly volume-weighted averages were tested to see whether the data were normally distributed or log-normally distributed. If the data were determined to not have a normal distribution, the data were presented arithmetically for means and standard deviations and non-parametric tests applied for trend analysis. All other parameters were also tested for normality but not volume weighted. Normality test results can be found in Appendix D. All data were analyzed for year-to-year differences during the study period and within seasons. Seasons were defined as winter (January through March), spring (April through June), summer (July through September), and fall (October through December). Tables 4 and 5 present a summary of whole-lake, nearshore, and pelagic averages and ranges for the 1990 through 2001 Lake Washington water quality monitoring data. Table 6 summarizes the results of the trend analysis performed for each parameter. Data collected at the deep station, 0852, is used to represent the overall water column profile characteristics of the lake. Station 0852 is the same location as the long-term study site used by Edmondson at the University of Washington.

Data collected from 1990 through 2001 indicate that the quality of Lake Washington's water supports beneficial uses such as direct water contact recreation, fishing, wildlife, and fisheries as defined by WAC 173-201A. Some of the major findings are as follows:

- Temperature of Lake Washington ranged from 7º to 9ºC in January during the period of complete mixing every year. The maximum temperature in both nearshore and pelagic water was between 21.5ºC and 24.5ºC without an increasing trend. From 1993 to 2001 there was an increasing trend in seasonal and annual average water temperatures (epilimnetic and whole lake) that may be attributed to global climate change-related increases in air temperatures. The effect of this trend on lake biota is currently unknown.
- Transparency has remained consistent from year to year, with the 10-year lake-wide annual average of 4.6 m and the mean summer transparencies ranging from 3.5 to 5.6 m.
- DO concentrations indicate that Lake Washington is mesotrophic, which is an improvement from the 1950s and 1960s when it was eutrophic.
- Annual whole-lake volume-weighted mean TP concentrations ranged from 10 to 18 μg/L and were lower in the last 4 years of the study. The TP concentrations in the lake are indicative of a mesotrophic condition. The 10-year annual mean TP was 14 μg/L. External loading of P determines P concentrations in the lake. Internal loading of P is not a significant part of the P cycle in the lake.
- The annual whole-lake TN mean concentrations ranged between 175 to 340 μg/L.
- N:P ratios were above 7:1, ranging from 13:1 to 30:1, indicating P limitation.
- The annual chl *a* 12-year mean was 3.4 μg/L, with a summer 12-year mean of 2.4 μg/L. These concentrations indicate that the lake is mesotrophic.

Lake Washington appears to be in stable ecological condition with respect to water quality following the pre-sewer diversion period of over-enrichment. The lake is sensitive to P loading, and the maintenance of present day water quality is dependent on P loading remaining at or near current levels. Currently, the low P input from the largest source of water to the lake, the Cedar River, is key to maintaining lake quality. Maintenance of the generally rural lower reaches and the protected upper watershed is critical.

Table 4. Summary of Nutrient and Dissolved Oxygen Data, Including Study Period Annual Volume-Weighted Whole-Lake, Nearshore, and Pelagic Means, Ranges, and Seasonal Means Where Applicable

Parameter	Study Period Annual Volume-Weighted Mean			Range of Volume-Weighted Annual Means	Study Period Seasonal Volume-Weighted Mean							
	Whole-Lake[1] 1992-2001	Nearshore 1990-2001	Pelagic[1] 1992-2001		Whole-Lake 1992-2001				Nearshore 1990-2001			
					W	Sp	S	F	W	Sp	S	F
Stratified Hypolimnetic Dissolved Oxygen, mg/L	n/a	n/a	8.6	8.9-7.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Total Phosphorus, µg/L	14	19	13	10-25	16	14	13	15	27	21	17	15
Soluble Reactive Phosphorus, µg/L	6	6	6	2-11	8	4	5	7	11	4	4	5
Total Nitrogen[2], µg/L	278	335	267	160-390	287	288	273	277	458	371	249	279
Nitrate-Nitrite, µg/L-N	162	148	163	99-215	193	149	144	161	302	138	50	99
Ammonium-Nitrogen, µg/L	14	17	13	3-29	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

W = winter, Sp = spring, S = summer, F = Fall

1 Water samples were not collected at deep stations before 1992; therefore, whole-lake and pelagic means were not calculated in 1990 or 1991.

2 Total nitrogen samples were not collected until spring of 1993. therefore, there is no 1992 data or winter of 1993 data.

Table 5. Summary of Non-Nutrient Data, Including Study Period Annual Whole-Lake, Nearshore, and Pelagic Means and Ranges

Parameter	Study Period Annual Mean			Range of Annual Means
	Whole-Lake[1] 1992-2001	Nearshore 1990-2001	Pelagic[1] 1992-2001	
Temperature, °C	12	13	12	11-15
Secchi depth[2], m	4	4	5	4-5
Conductivity[3], µmhos/cm	n/a	n/a	n/a	60-173
pH[3]	n/a	n/a	n/a	6.4-9.2
Alkalinity, mg/L $CaCO_3$	n/a	n/a	36[4]	26-46
Chlorophyll *a*, µg/L	3	4	3	2-5

1 Water samples were not collected at any deep stations before 1992; therefore, whole-lake and pelagic means were not calculated in 1990 or 1991.

2 June to September Secchi depths were used to calculate annual means and the study period annual mean.

3 Annual, seasonal, and study period means were not calculated for conductivity and pH; only ranges were determined.

4 Annual mean alkalinity was only calculated for Station 0852.

Table 6. Summary of Statistical Data Analysis for Long-term Trends and Comparison of Nearshore Versus Pelagic Sites[a]

Parameter	Long-term Trend Analysis			Comparison Nearshore vs. Pelagic[b]	Seasonal Difference[b]
	Whole-Lake (n)	Nearshore (n)	Pelagic (n)		
Annual Mean Temperature (1993 to 2001)	+(9)[c]	+(9)[c]	+(9)[c]	No difference	n/a
June-Sept. Mean Secchi Transparencies (1990-2001)	0(10)[c]	0(10)[c]	0(10)[c]	No difference	Fall different from winter and spring
Stratified Period Hypolimnetic Dissolved Oxygen (1993-2001)	n/a	n/a	0(6)[b]	n/a	n/a
pH	n/a	n/a	n/a	No difference	n/a
Annual Mean Total Phosphorus (1993-2001)	-(9)[c]	0(9)[c]	-(9)[c]	Nearshore > Pelagic	n/a
Annual Mean Soluble Reactive Phosphorus (1993 to 2001)	-(12)[b]	-(12)[b]	-(12)[b]	No difference	n/a
Annual Mean Total Nitrogen (1993-2001)	0(9)[c]	0(9)[c]	0(9)[c]	Nearshore > Pelagic	n/a
Annual Mean Nitrate/Nitrite-Nitrogen (1990-2001)	0(9)[b]	0(9)[b]	0(9)[b]	No difference	n/a
Annual Mean Ammonium-Nitrogen (1993-2001)	0(12)[b]	0(12)[b]	0(12)[b]	No difference	n/a
Annual Mean TN:TP Ratios (1994-2001)	+(8)[c]	n/a	n/a	n/a	n/a
Annual and Seasonal Mean Chlorophyll *a* (1990-2001)	0(9)[c]	0(12)[c]	0(9)[c]	No difference	Spring higher

a Increasing trend is designated by "+", no trend by "0" and decreasing trend by "-". Numbers in parentheses (n) indicate the number of samples.

b Statistical trends were determined using an ANOVA test. Annual means, monthly means, and/or seasonal means were used to determine a trend or difference.

c Statistical trends were determined using the Kendall rank correlation test. Annual means were used to determine a trend.

4.1. Physical Conditions

4.1.1. Temperature

Lake Washington is a monomictic lake that is isothermal and undergoes complete mixing from the surface to bottom during December through March. In April, the lake begins to stratify, and by June it is strongly stratified and remains so until October. At this time, surface water cools and stratification of the lake starts to weaken until the thermal stratification that physically separates the surface waters from the deeper waters breaks down, allowing the entire water column to mix. The 9-year period of record for the temperature data is presented in Figure 4 for the deep station (0852). Data illustrated in this figure are typically representative of vertical stratification and mixing patterns within the lake. The temperature patterns observed at this station and illustrated in Figure 4 are similar to the pattern observed at the other stations. The minimum recorded temperature between 1990 and 2001 was 5.2ºC, indicating the lake does not freeze. Historical data, as well as data shown in Figure 4, indicate that the lake is completely mixed in January at a temperature between 7º and 9ºC.

Figure 5 presents the annual maximum temperatures recorded from 1990 through 2001. No difference in high temperatures was found between nearshore and pelagic areas, nor was there a trend toward increasing or decreasing annual maximum epilimnetic temperatures ($p < 0.05$). However, an increasing trend was found for annual mean temperatures for whole-lake, nearshore, and pelagic areas between 1993 and 2001 ($p < 0.05$, $n = 9$, annual means). No trend was identified between 1992 and 2001for the same areas ($p < 0.05$, $n = 10$, annual means). As seen in Figure 6, the mean annual temperatures for whole-lake, nearshore, and pelagic areas have standard deviations that are overlapping between years. Several more years of monitoring will be required to quantify if any long-term warming trend exists.

The seasonal temperature means shown in Figures 7 and 8 indicate that temperatures throughout the lake were below critical levels for salmonid species (17.8ºC; Kerwin, 2001) for fall, winter, and spring. Summer means for the nearshore area from 1990 through 2001 and in 1992 for the pelagic area did exceed 17.8ºC. However, the majority of pelagic summer means were less than 16ºC. The temperature in the nearshore areas between the surface and 9 m depth exceeded 17.8ºC from mid-July through early October most years, perhaps limiting fish utilization of these areas at these times.

At any given time, the majority of the water volume is between 6º and 9ºC. Below 25 m, the water temperature is rarely greater than 10ºC and is often less. The high temperature on the surface was 24.5ºC during the study period.

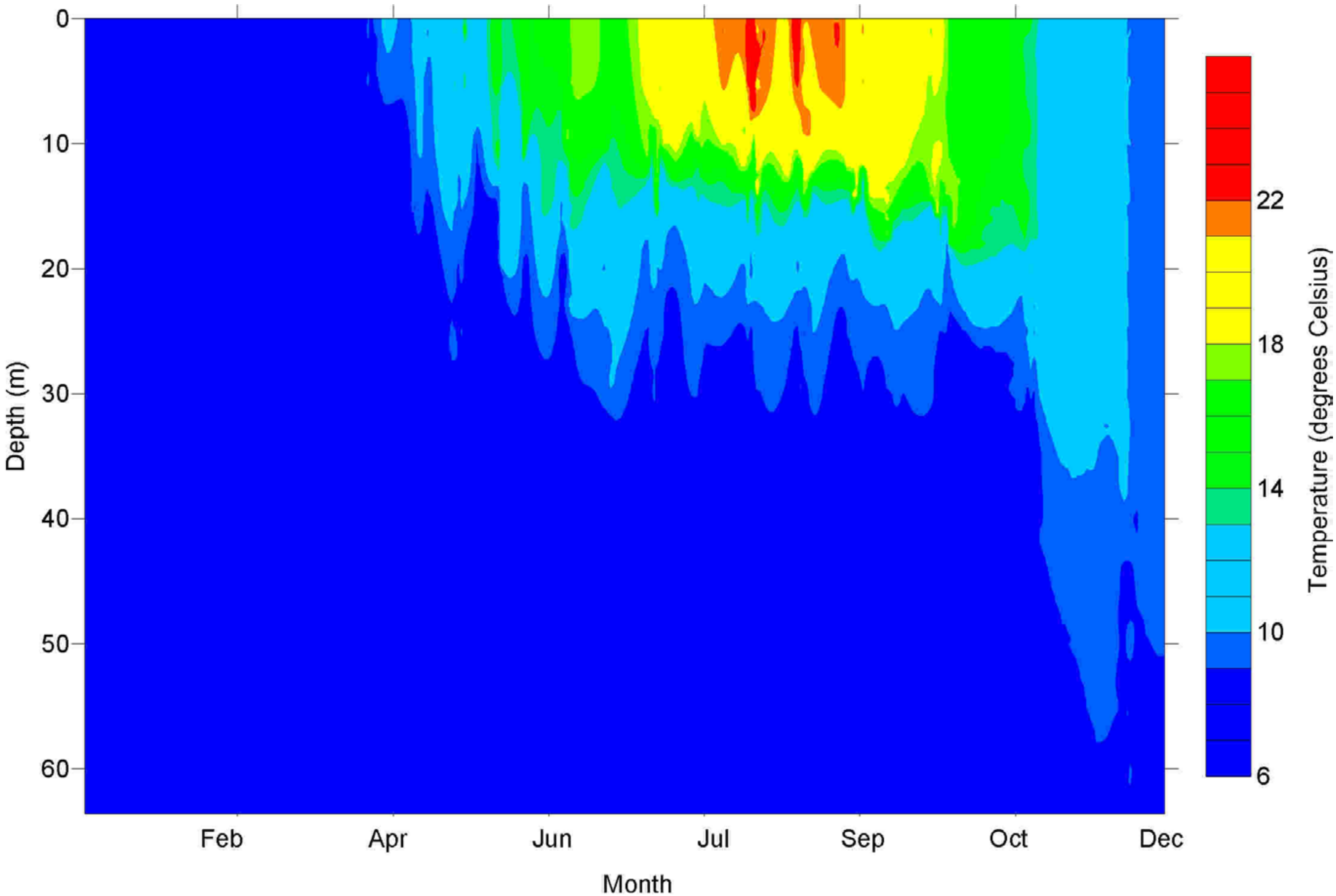

Figure 4. Annual Temperature Profile of Lake Washington Based on a Combined 9-Year Period of Record From 1993 to 2001 at the Deep Lake Station (0852)

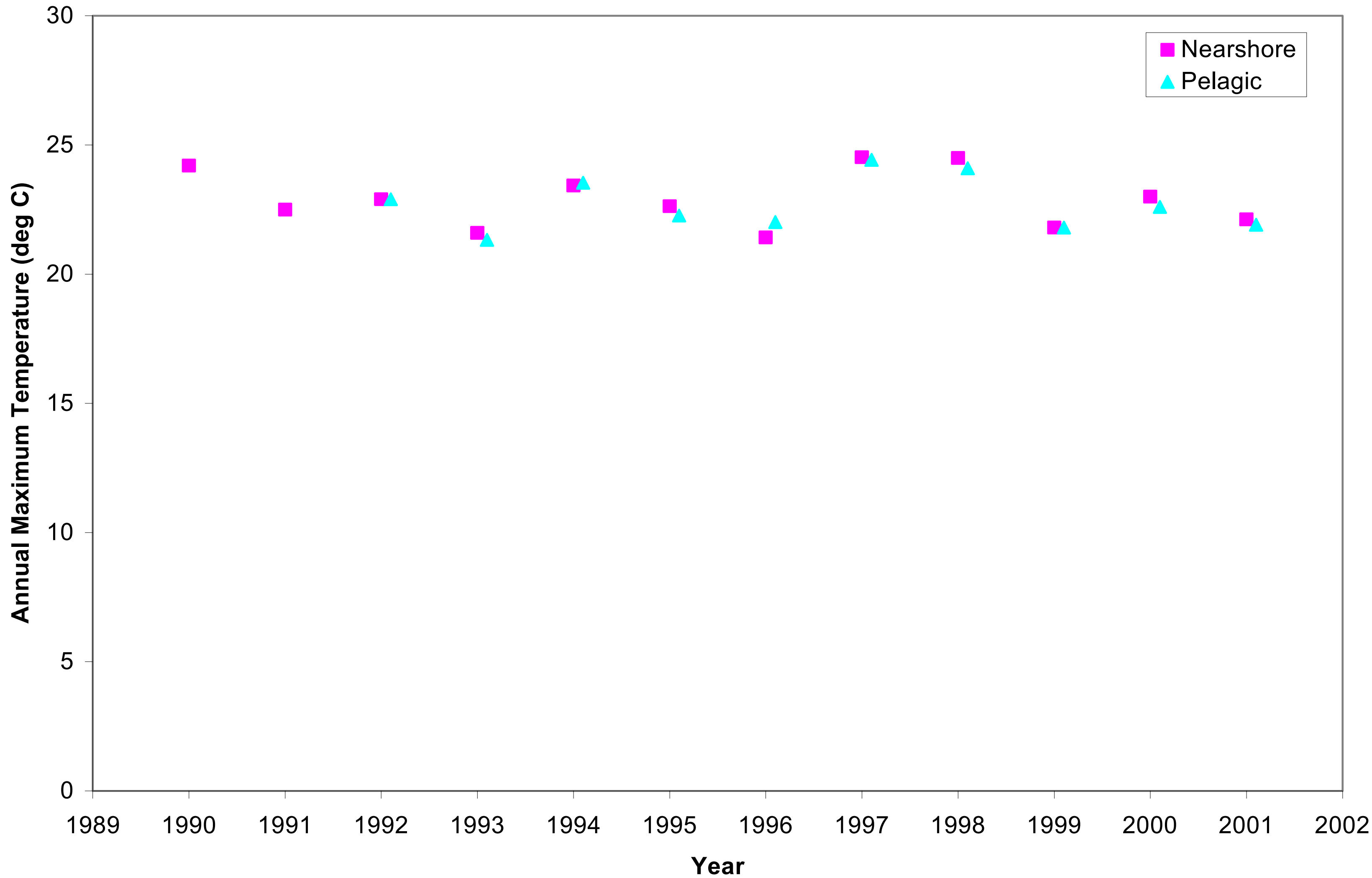

Figure 5. Annual Maximum Recorded Temperature in the Epilimnetic Waters of Lake Washington From 1990 to 2001

Note: Means are arithmetic.

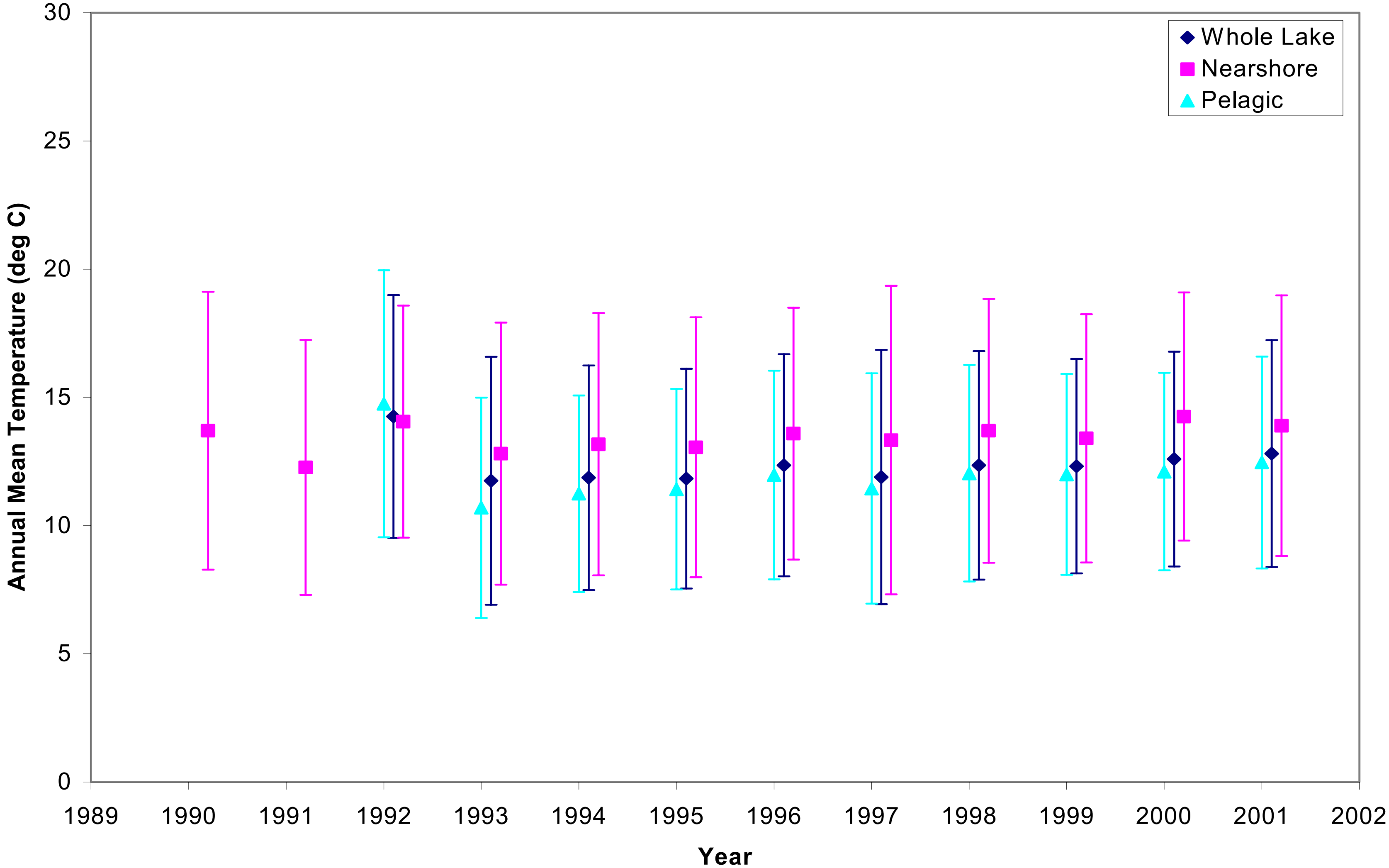

Figure 6. Annual Mean Whole-Lake, Nearshore, and Pelagic Temperature for Lake Washington From 1990 to 2001

Note: Means +/- SD are arithmetic.

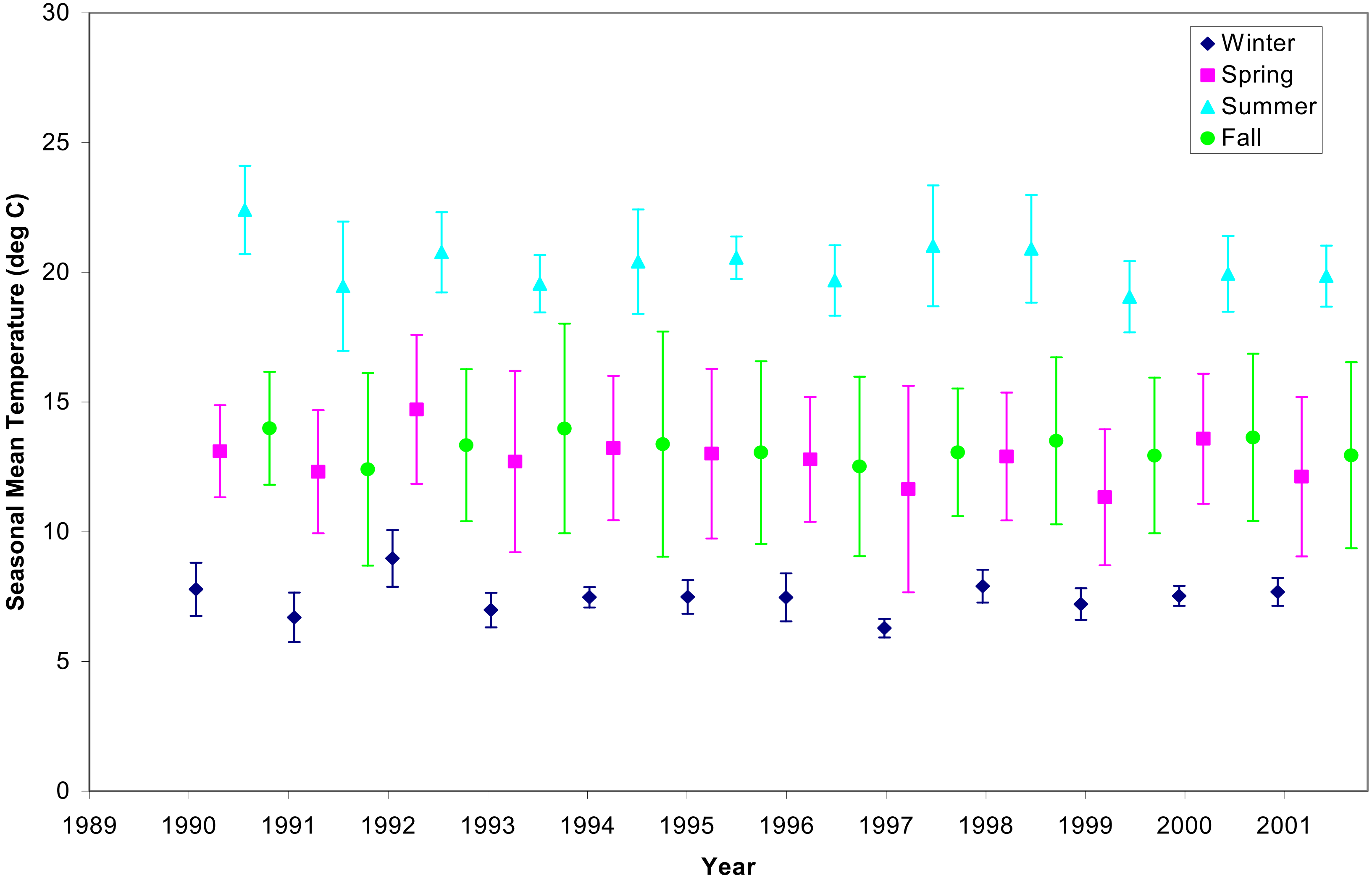

Figure 7. Seasonal Mean Temperature for Lake Washington Nearshore Areas From 1990 to 2001

Note: Means +/- SD are arithmetic.

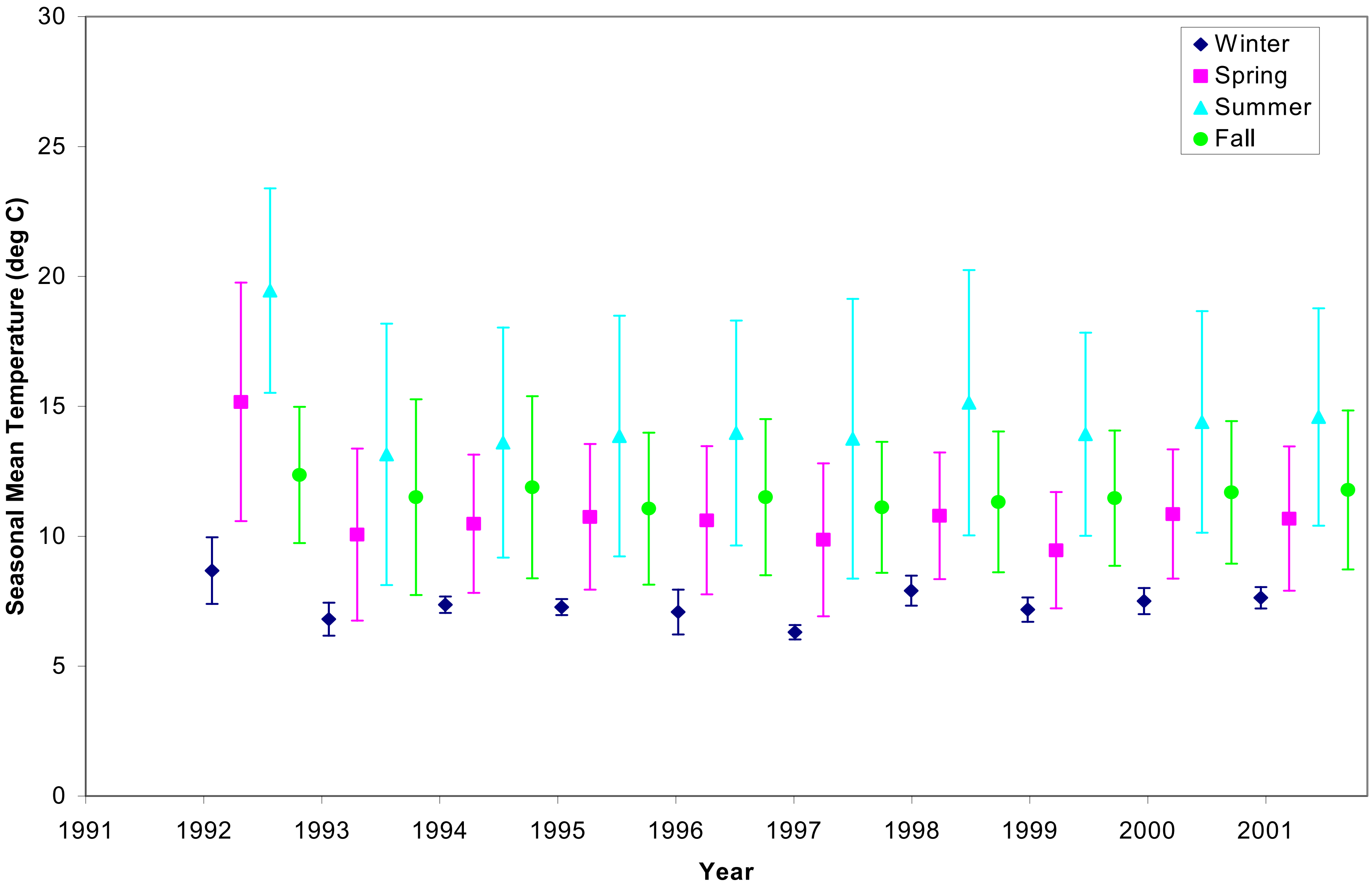

Figure 8. Seasonal Mean Temperature for Lake Washington Pelagic Areas From 1992 to 2001

Note: Means +/- SD are arithmetic.

4.1.2. Transparency

Mean summer (June through September) transparency in the pelagic areas of Lake Washington ranged from 3.5 to 5.6 m from 1992 to 2001, with a 10-year mean of 4.6 m at the pelagic stations (Figure 9). Transparency data for June through September (rather than July through September) were used so that recent King County measurements could be compared with past data from University of Washington investigators. Mean transparency in the pelagic area for July through September was nevertheless the same as June through September. Means from the nearshore stations were slightly less, by 0.1 to 0.5 m, than those in the pelagic area. However, that difference was not statistically significant ($p < 0.05$). Greater transparency in the deep, pelagic area is expected given that nearshore areas are closer to inflows as well as being subject to bottom disturbance from wind and wave action.

Except for 1999, summer mean transparencies in the pelagic area were greater in 3 of the last 4 years, by an average of about 1 m, than the early part of the decade (Figure 9). However, given the year-to-year variation of over a meter, a longer time period is needed to determine if a trend toward greater transparency is actually occurring. An ANOVA did not show that the summer means for these years (1998, 2000, and 2001) were significantly greater ($p < 0.05$, $n = 4$, summer monthly means) than summer means in the previous years. A Kendall rank correlation test ($n = 10$, annual means for the 10-year period, $p < 0.05$) also showed no trend to greater transparency in the pelagic area of Lake Washington.

Whole-lake mean transparency in the fall was usually greater than for other seasons. Summer transparency (July through September) was also greater than in winter and spring, and in most years summer transparency was similar to fall (Figure 10). Fall transparency was significantly different from winter and spring (ANOVA; $p < 0.05$, $n = 10$, seasonal means for 10-year period), but not significantly different from summer means (ANOVA; $p < 0.05$, $n = 10$, seasonal means for the 10-year period). Inflows carrying non-algal particulate matter are generally less during summer and fall. Also, stratification during summer and early fall allow the settling of algal and non-algal material from the epilimnion without replenishment from bottom waters. The opposite process, (i.e., complete mixing and higher inflows), occurs during winter and spring, so this seasonal variation was expected. The largest algal increase usually begins in March. Trends are not evident for any season given the year-to-year variation, as is the case for pelagic or nearshore stations when treated separately.

There is an observable difference between transparency measurements by the Department of Zoology, University of Washington (UW) and King County at the deep station, 0852 (Figure 11). The UW measurements were consistently greater by an average of 1.9 m than those measured by King County from 1993 to 2001. The 9-year mean measured by UW was 6.5 m compared to 4.5 m by King County. A difference of that magnitude is much greater than expected from random sampling error, and indicates a bias in methods. Secchi measurements vary among individuals under constant conditions by a few tenths of a meter at most (visual acuity varies). The consistently higher UW measurements are probably too great to be due to sample frequency, which was twice per month by UW and has ranged from once to twice per month by King County. One factor that may account for the difference is the distance from the water surface to the reader's eye, which is less than 1 foot by UW and about 5 feet by King County, due to differences in boat gunnel height. Viewing distance and variability of marked eye measurements has been addressed by Smith (2001), and he concluded that a view box is needed to reduce variability between measurements. However, that effect has not been examined by King County (Droker, 2002 personal communication). UW uses an all white disk for historical consistency, while King County uses the more standard black and white disk, which should provide more contrast and, hence, sensitivity and accuracy. However, a direct comparison elsewhere showed that measurements with a white disk were greater than a black and white one, but only by a few tenths of a meter (Carlson, 2002 personal communication). Both techniques resulted in means that were greater than 3.6 m, which is the threshold for mesotrophic versus eutrophic conditions (Carlson, 1977).

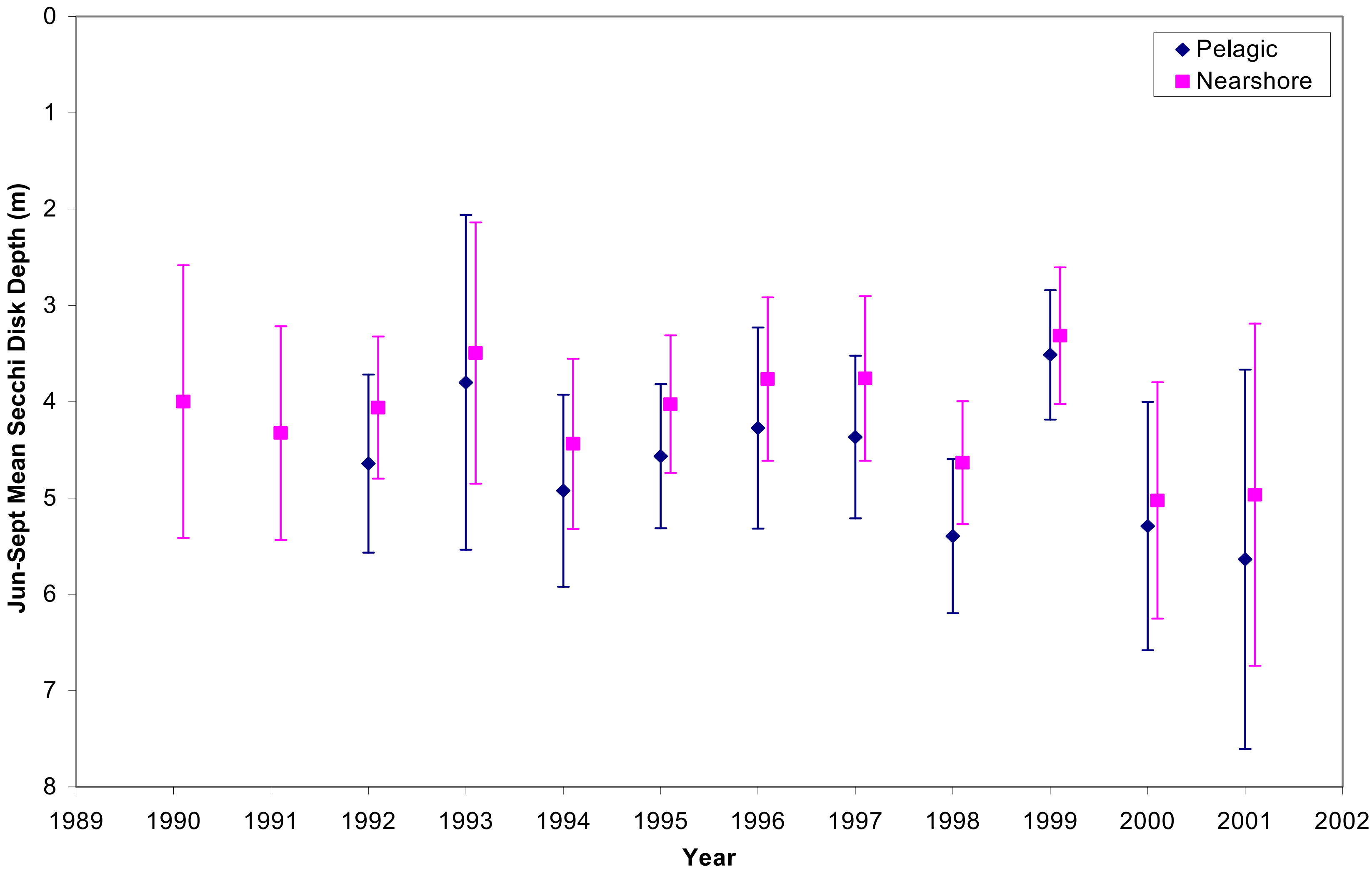

Figure 9. June Through September Mean Transparency (Secchi Depth) in Lake Washington From 1990 to 2001

Note: Means represent five pelagic and seven nearshore stations and are +/- SD.

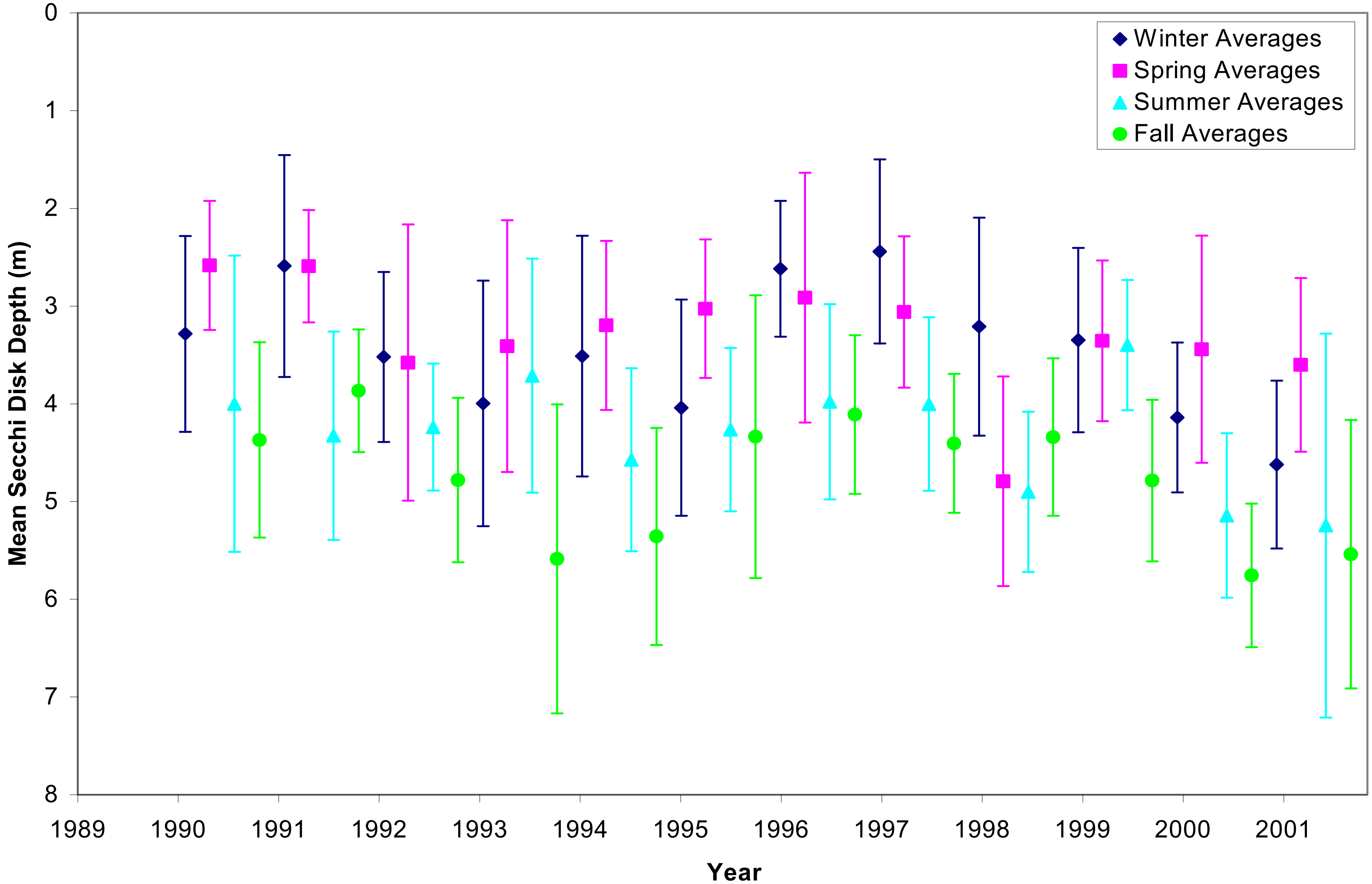

Figure 10. Seasonal Mean Transparency for All 12 Stations in Lake Washington From 1990 to 2001

Note: Means +/- SD.

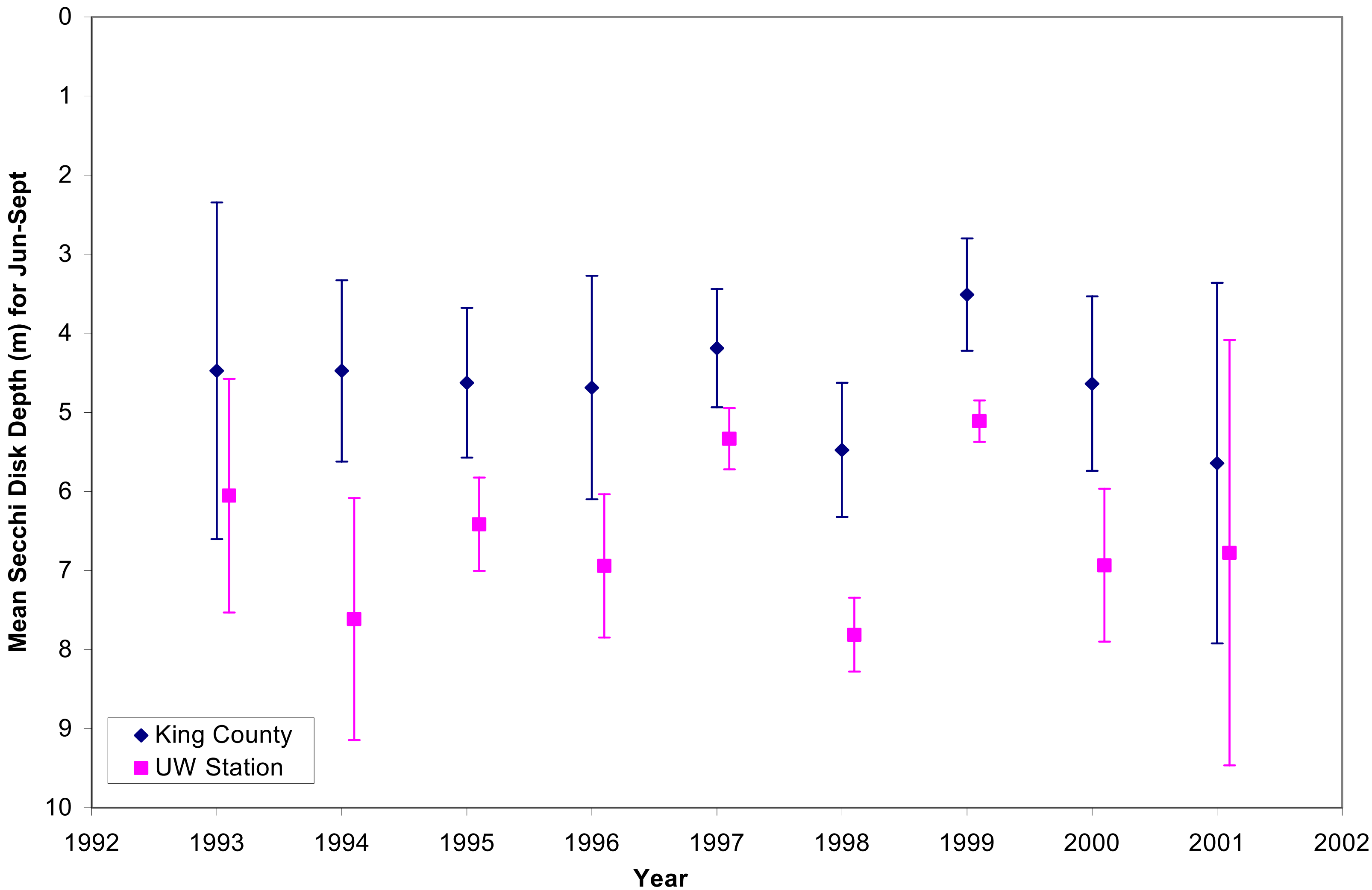

Figure 11. Comparison of June Through September Mean Transparency Measured by the University of Washington Department of Zoology and King County DNR at the Deep Station (0852) in Lake Washington From 1993 to 2001

Note: Means +/- SD.

4.2. Chemical Conditions

4.2.1. Dissolved Oxygen

DO concentrations have been recorded in Lake Washington for more than 50 years. Hypolimnetic DO has proven to be a sensitive indicator of the lake's condition, whereas epilimnetic DO has not been as useful a predictor of trophic state. DO in the epilimnion of stratified lakes is either near saturation with the atmosphere, or it varies greatly over diurnal periods if the lake is highly enriched. Epilimnetic DO concentrations in Lake Washington determined from mid-day during the 1990s were near saturation and confirm that the lake is no longer highly enriched. Beyond that, epilimnetic DO measurements are of limited use as a long-term index of water quality conditions.

Hypolimnetic DO concentration (concentrations measured at > 25 m during stratification) and areal hypolimnetic oxygen deficit rate (AHOD) are excellent indicators of lake condition, and the latter is also an index of trophic state (see Section 4.4). Specifically, AHOD is a measure of the oxygen depletion rate in the hypolimnion per sediment area per day and is expressed as mg DO/m^2-day. The greater the AHOD, the more eutrophic (enriched) the lake. The lower the AHOD, the more oligotrophic the lake. Lake Washington's AHOD was calculated for the stratified period (May through October) from 1993 to 2001. (DO data were insufficient to calculate AHOD from 1990 to 1992.) The AHOD rate was determined by multiplying the slope of the line defining the best fit for values of volume-weighted, hypolimnetic DO concentration related with time (g DO/m^3-day) by the hypolimnetic zone (> 25 m) mean depth (19 m). The resulting AHOD has units of g DO/m^2-day; multiplying by 1,000 mg/g gives mg/m^2-day. Arithmetic means were used for calculating AHOD, because that is conventional procedure, and May through October DO concentrations were normally distributed.

From 1993 to 2001, hypolimnetic mean DO ranged from 7.7 to 8.9 mg/L, and AHOD ranged from 285 to 564 mg/m^2-day (Figure 12). The 9-year mean AHOD was 473 ± 89 mg/m^2-day. Neither the calculated AHOD nor the hypolimnetic mean DO show an observable trend during this period, nor do statistical tests show a significant difference among annual stratified-period mean DO concentrations (ANOVA; $p < 0.05$, $n = 6$, stratification monthly means). AHOD values are single values for each year, and thus have no variance, which is needed for statistical testing. Because the within-year, stratified-period hypolimnetic DO variability was high, the stratified-period DO means did not exhibit a significant difference among years.

A rate of 550 mg/m^2-day or greater was suggested to indicate a eutrophic state by Mortimer (1941). That criterion was recently reevaluated and set at 400 mg/m^2-day (Nurnberg, 1996). Hence, Lake Washington can be considered mesotrophic or eutrophic from the standpoint of its AHOD, depending on criteria used. Although there appears to be no trend in AHOD during this last 11-year period of interest, there was a substantial decrease since the pre-diversion and early post-diversion years. The recent values are about half the high rate prior to wastewater diversion; AHOD in 1964 was 810 mg/m^2-day (Welch and Perkins, 1979b). In addition, the AHOD values from 1993 to 2001 were